

# TOPICS IN CP VIOLATION

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## Abstract

I briefly review some results and open questions in the analysis of CP violation in the B sector.

## 1 Introduction

Although we know since almost forty years that CP is violated, we still have a lot to learn about the mechanisms of such a violation. In particular, we do not know whether the Standard Model of elementary particle Physics (SM) provides an adequate description of this phenomenon. CP violation is one of the necessary conditions to explain matter/antimatter asymmetry starting from initially symmetric conditions in the early Universe. Moreover, baryogenesis requires sources of CP violation beyond SM and actually almost all new Physics scenarios provide such new sources. Therefore, CP violation is an efficient testing ground for the SM. CP violation was observed first in neutral kaon decays through the detection of the mode  $K_L \rightarrow \pi\pi$  [1]. One defines  $\epsilon = \frac{A(K_L \rightarrow \pi\pi(I=0))}{A(K_S \rightarrow \pi\pi(I=0))}$ , i.e. the ratio of a CP suppressed decay to a CP allowed one. The experimental measure:  $|\epsilon|_{exp} = (2.271 \pm 0.017) \times 10^{-3}$  [2] probes the mechanism of *indirect* CP violation, due to the fact that the particles taking part into weak processes are not CP eigenstates, although the amplitudes themselves do not violate CP. The kaon phenomenology provided us also with the first measure of *direct* CP violation, i.e. directly at the decay amplitude level, through the measure of  $\text{Re}(\epsilon'/\epsilon) = (1.8 \pm 0.4) \times 10^{-3}$

[2]. From the theoretical side, many uncertainties affect the calculation of this parameter, essentially linked to the matrix elements of the effective weak hamiltonian  $H_{eff}(\Delta S = 1)$  between the kaon and a two pion state.

Within the SM, the only source of CP violation is the Cabibbo-Kobayashi-Maskawa matrix  $V_{CKM}$  which describes the mixing of down-type quarks in charged current interactions. In the most general pattern,  $V_{CKM}$  depends on four parameters, one of which is a complex phase. In the Wolfenstein parametrization they are  $\lambda, A, \rho$  and the complex phase  $\eta$ .

The SM requires  $V_{CKM}$  to be unitary. The unitarity relation  $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$  can be represented as a triangle in the  $(\bar{\rho}, \bar{\eta})$  plane, where  $\bar{\rho} = \rho(1 - \lambda^2/2)$ ,  $\bar{\eta} = \eta(1 - \lambda^2/2)$ , as shown in Fig. 1. The angles are linked

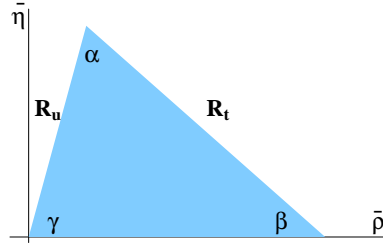


Figure 1: Unitarity Triangle

to the phases of the CKM elements through the relations:

$$\alpha = \text{Arg} \left( -\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right) \quad \beta = \text{Arg} \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right) \quad \gamma = \text{Arg} \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right) . \quad (1)$$

Many efforts are devoted to determine  $\alpha, \beta, \gamma$  and constrain the upper vertex of the triangle. The measure of  $\epsilon$  constrains such a vertex in a region of the  $(\bar{\rho}, \bar{\eta})$  plane determined by two hyperbolae. Analogously, semileptonic B decays give information about the length  $R_u$  of the left side, providing again a region for the apex. More constraints can be obtained from the B phenomenology. Many reviews are available on this subject [3], here we shall briefly recall some results and open questions in the B sector.

## 2 CP violation in the system of neutral $B$ mesons

Neutral B mesons mix with each other, the mixing being described by a box diagram dominated by the intermediate top exchange contribution, with  $\text{Arg}(\text{box}) = 2 \text{Arg}[V_{td}V_{tb}^*] = 2\delta^m = 2\beta$  (for  $B_s$  system:  $\delta_s^m = \text{Arg}[V_{ts}V_{tb}^*]$ ). Due

to oscillations, the system evolves and time-dependent CP-asymmetries can be considered. It is particularly convenient to consider decays into a CP eigenstate  $f_{CP}$  in which both  $B^0$  and  $\bar{B}^0$  can decay. The asymmetry reads:

$$\begin{aligned} a_{f_{CP}} &= \frac{\Gamma(B^0(t) \rightarrow f_{CP}) - \Gamma(\bar{B}^0(t) \rightarrow f_{CP})}{\Gamma(B^0(t) \rightarrow f_{CP}) + \Gamma(\bar{B}^0(t) \rightarrow f_{CP})} = \\ &= \frac{(1 - |\lambda|^2)\cos(\Delta mt) - 2\text{Im}\lambda\sin(\Delta mt)\eta_f}{1 + |\lambda|^2} = \\ &= C_{f_{CP}}\cos(\Delta mt) - S_{f_{CP}}\sin(\Delta mt) \end{aligned} \quad (2)$$

where  $\lambda = e^{-2i\delta^m} \bar{A}/A$  and  $\mathcal{A}(B^0 \rightarrow f_{CP}) = A$ ,  $\mathcal{A}(\bar{B}^0 \rightarrow f_{CP}) = \bar{A}$ ;  $\eta_f$  is the CP-parity of the state  $f_{CP}$ . In general, one may write:  $A = \sum_i A_i e^{i\delta_i} e^{i\phi_i}$ ,  $\bar{A} = \sum_i A_i e^{i\delta_i} e^{-i\phi_i}$ , the  $\delta_i$  being strong phases, the  $\phi_i$  weak ones. The term  $C_{f_{CP}}$  probes direct CP violation, being zero if  $|\lambda| = 1$ , i.e. if  $|\bar{A}| = |A|$ , while the term  $S_{f_{CP}}$  probes mixing-induced CP violation.

Special cases occur when  $\forall i : \phi_i = \phi$ , so that  $|\bar{A}| = |A|$ ,  $|\lambda| = 1$  and  $a_{f_{CP}} = -\text{Im}\lambda\sin(\Delta mt)\eta_f$ , with  $\text{Im}\lambda = -\sin[2(\delta^m + \phi)]$ . Before considering which modes are suitable to extract the angles of the unitarity triangle, it should be recalled that also the measure of the oscillation parameters  $\Delta m_q$ ,  $\Delta m_s$  provide constraints in the  $(\bar{\rho}, \bar{\eta})$  plane. The mass difference in the B ( $B_s$ ) system can be obtained from the box diagram with virtual top exchange, so that  $\Delta m_d \propto |V_{td}|^2$ ,  $\Delta m_s \propto |V_{ts}|^2$ . From the world average:  $\Delta m_d = 0.502 \pm 0.006 \text{ ps}^{-1}$  and the bound:  $\Delta m_s > 14.4 \text{ ps}^{-1}$ , other regions can be selected, which are circles centered at  $(1, 0)$ .

### 3 Strategies to extract $\alpha$ , $\beta$ , $\gamma$

Among the angles of the triangle,  $\beta$  has been the first one which has been experimentally measured through the observation of the time dependent CP asymmetry in  $B_d^0 \rightarrow J/\psi K_S$ . Within the SM, this process is induced at quark level by the transition  $\bar{b} \rightarrow \bar{c}c\bar{s}$ , proceeding through tree and penguin diagrams. The penguin with up-quark exchange is subleading in the Wolfenstein parameter  $\lambda$ , so that, neglecting its contribution, the amplitude is dominated by a single weak phase, i.e. that of  $V_{cb}V_{cs}^*$ , which is real to a very good approximation. This means that the time dependent asymmetry provides just  $\sin(2\beta)$ , and hence  $2\beta$  up to a twofold ambiguity. The world average of the experimental determinations is dominated by the most recent Belle and BABAR data [4] and reads:  $\sin(2\beta) = 0.736 \pm 0.049$ , giving  $2\beta = (47 \pm 4)^\circ$  or  $2\beta = (133 \pm 4)^\circ$ . The first solution is in good agreement with the indirect

determination obtained through the CKM fits [5], although one cannot exclude *a priori* the second one, which would signal new physics effects. The resolution of this discrete ambiguity has been subject of several works [6]. A possibility is to consider the modes  $B^0(\bar{B}^0) \rightarrow D^+D^-\pi^0(K_S)$ , assuming that they proceed through intermediate S-wave and P-wave charmed and beauty resonances [7, 8]. The variables  $s_+ = (p_{D^+} + p_\pi)^2$  and  $s_- = (p_{D^-} + p_\pi)^2$  can be introduced, in terms of which the time dependent amplitudes read as

$$\begin{aligned} |\mathcal{A}(B^0(t) \rightarrow D^+D^-\pi^0)|^2 &= \frac{e^{-\Gamma t}}{2} [G_0(s_+, s_-) + G_c(s_+, s_-)\cos(\Delta mt) \\ &\quad - G_s(s_+, s_-)\sin(\Delta mt)] \\ |\mathcal{A}(\bar{B}^0(t) \rightarrow D^+D^-\pi^0)|^2 &= \frac{e^{-\Gamma t}}{2} [G_0(s_-, s_+) - G_c(s_-, s_+)\cos(\Delta mt) \\ &\quad + G_s(s_-, s_+)\sin(\Delta mt)] \end{aligned} \quad (3)$$

where

$$\begin{aligned} G_0(s_+, s_-) &= |A(s_+, s_-)|^2 + |\bar{A}(s_+, s_-)|^2 \\ G_c(s_+, s_-) &= |A(s_+, s_-)|^2 - |\bar{A}(s_+, s_-)|^2 \\ G_s(s_+, s_-) &= -2\sin(2\beta)\text{Re}[A^*(s_+, s_-)|\bar{A}(s_+, s_-)] \\ &\quad + 2\cos(2\beta)\text{Im}[A^*(s_+, s_-)|\bar{A}(s_+, s_-)] \end{aligned} \quad (4)$$

and  $A(s_+, s_-) = \mathcal{A}(B^0 \rightarrow D^+D^-\pi^0)$ ,  $\bar{A}(s_+, s_-) = \mathcal{A}(\bar{B}^0 \rightarrow D^+D^-\pi^0)$ . From (4) one can see that it is possible to access to  $\cos(2\beta)$ . The estimated branching ratios [8] also make their experimental detection rather promising.

An interesting test can be carried out considering the mode  $B_d \rightarrow \phi K_S$  since its CP asymmetry should coincide, within the SM, with that of  $B_d \rightarrow J/\psi K_S$ . Recent results give [9]:

$$\begin{aligned} C_{\phi K_S}^{BABAR} &= -0.80 \pm 0.38 \pm 0.12 & S_{\phi K_S}^{BABAR} &= -0.18 \pm 0.51 \pm 0.07 \\ C_{\phi K_S}^{BELLE} &= 0.15 \pm 0.29 \pm 0.07 & S_{\phi K_S}^{BELLE} &= 0.96 \pm 0.50_{-0.09}^{+0.11}. \end{aligned} \quad (5)$$

Since for  $B_d \rightarrow J/\psi K_S$   $C_{\psi K_S} = 0$ ,  $S_{\psi K_S} = -\sin(2\beta)$ , the results (5) might represent hints of new physics, although the large uncertainties prevent from drawing any conclusion. Since the determination of  $\sin(2\beta)$  from  $B_d \rightarrow J/\psi K_S$  and the indirect one from the fits agree with each other, eventual new physics would affect the transition  $\bar{b} \rightarrow \bar{s}s\bar{s}$  more likely than  $\bar{b} \rightarrow \bar{c}c\bar{s}$  and hence signals should be detected also in other modes, such as  $B_d \rightarrow \eta' K_S$ , for which preliminary results agree with those from  $B_d \rightarrow J/\psi K_S$ .

Let us now consider the status of the determination of  $\alpha$ . Within the SM, if penguin contributions could be neglected, it would be possible to get  $\alpha$  from  $B_d \rightarrow \pi^+\pi^-$ . In this case, one would have  $C_{\pi\pi} = 0$  and  $S_{\pi\pi} = \sin(2\beta + 2\gamma) = -\sin(2\alpha)$ . However, penguins are not negligible and should be taken into account. The B factories provide us with the results [10, 11]:

$$\begin{aligned} C_{\pi\pi}^{BELLE} &= -0.77 \pm 0.27 \pm 0.08 & S_{\pi\pi}^{BELLE} &= -1.23 \pm 0.41^{+0.08}_{-0.07} \\ C_{\pi\pi}^{BABAR} &= -0.30 \pm 0.25 \pm 0.04 & S_{\pi\pi}^{BABAR} &= 0.02 \pm 0.34 \pm 0.03. \end{aligned} \quad (6)$$

In order to get rid of the penguin contribution, a fit procedure was adopted in [10], comparing the experimental results to theory; four parameters are involved:  $\beta$  which is taken from the direct measure of  $\sin(2\beta)$ ; the tree to penguin amplitude ratio  $|P|/|T|$ , varied according to theoretical estimates;  $\alpha$  and the strong phase difference between  $T$  and  $P$ . The result  $78^\circ \leq \alpha \leq 152^\circ$  is consistent with the range determined indirectly from the CKM fits.

The determination of  $\gamma$  is affected by theoretical uncertainties. We refer to [3] for a list of modes suitable to extract this phase. In order to consider strategies relevant for future machines, we discuss instead a proposal to obtain  $\gamma$  from  $B_c$  decays.  $B_c^-$  is the lowest lying  $b\bar{c}$  meson, discovered by CDF Collaboration in 1998 [12]. A large number of such particles will be produced at future hadron colliders and hence it is worthy to consider the possibility of studying CP violation through its decays. For this purpose, Fleischer and Wyler [13] considered the six decay modes:  $B_c^\pm \rightarrow D_s^\pm \{D^0, \bar{D}^0, D_+^0\}$ , where  $|D_+^0\rangle = (|D^0\rangle + |\bar{D}^0\rangle)/\sqrt{2}$  is the CP-even eigenstate. The following relations among the decay amplitudes hold:

$$\begin{aligned} \sqrt{2}\mathcal{A}(B_c^+ \rightarrow D_s^+ D_+^0) &= \mathcal{A}(B_c^+ \rightarrow D_s^+ D^0) + \mathcal{A}(B_c^+ \rightarrow D_s^+ \bar{D}^0) \\ \sqrt{2}\mathcal{A}(B_c^- \rightarrow D_s^- D_+^0) &= \mathcal{A}(B_c^- \rightarrow D_s^- D^0) + \mathcal{A}(B_c^- \rightarrow D_s^- \bar{D}^0). \end{aligned} \quad (7)$$

The amplitudes in (7) are roughly of the same order, since the colour suppressed mode  $B_c^+ \rightarrow D_s^+ \bar{D}^0$  is enhanced by  $V_{cb}$ , while the colour allowed  $B_c^+ \rightarrow D_s^+ D^0$  is suppressed by  $V_{ub}$ . This is the main difference with respect to the analogous  $B^\pm \rightarrow K^\pm D$  modes, where colour suppressed amplitudes are proportional to  $V_{ub}$ . Furthermore, the only weak phase involved is  $\gamma$ , so that the relations in (7) can be represented as two triangles with a common basis ( $\mathcal{A}(B_c^+ \rightarrow D_s^+ \bar{D}^0) = \mathcal{A}(B_c^- \rightarrow D_s^- D^0)$ ), but mismatched by  $2\gamma$ .

This method presents many advantages: the sides of the triangles have similar sizes and only tree diagrams are involved, contrarily to  $B \rightarrow K\pi$ , also considered to extract  $\gamma$ , where penguins are important [14]. Therefore,

comparing the results of the two methods would be a probe of new physics. Finally,  $B_c$  decays considered here are likely to be observed [15] at LHC, where a large number ( $\mathcal{O}(10^{10})$ ) of  $B_c$  per year are expected to be produced.

Among the strategies to over-constrain the unitarity triangle parameters, an important role will be played by  $B_s$  physics. Although  $B_s$  is non currently accessible at B factories, it will be copiously produced at hadron colliders. At present, the upper bound on  $\Delta m_s$  already constrains  $R_t$ , implying  $\gamma \leq 90^\circ$ . However, from  $B_s$  decays much more information could be gained, as from the mode  $B_s \rightarrow J/\psi\phi$ . In complete analogy with  $B_d \rightarrow J/\psi K_S$ , this decay will give access to the phase of  $B_s$  mixing.

## 4 Conclusions

Fig. 2 displays several constraints in the  $(\bar{\rho}, \bar{\eta})$  plane as reported by PDG, edition 2003 [2]. The resulting scenario shows no inconsistencies; in particular, the comparison between the direct determination of  $\sin(2\beta)$  and the indirect result of the CKM fits suggests that at present the SM describes coherently CP violation. Hence, one should look for small effects to reveal new physics, for example in  $b \rightarrow s$  penguins or in  $\Delta m_s$ . New observables may be studied to obtain further constraints and a reduction of theoretical uncertainties affecting the various predictions should be pursued, while waiting for more results in the LHC era.

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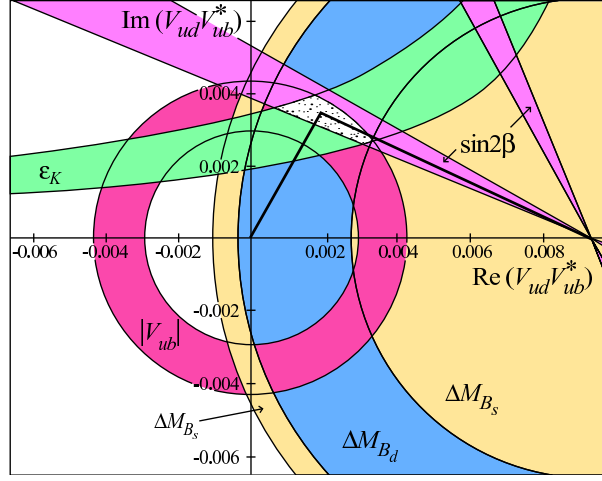


Figure 2: Constraints to the Unitarity Triangle from PDG [2].

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